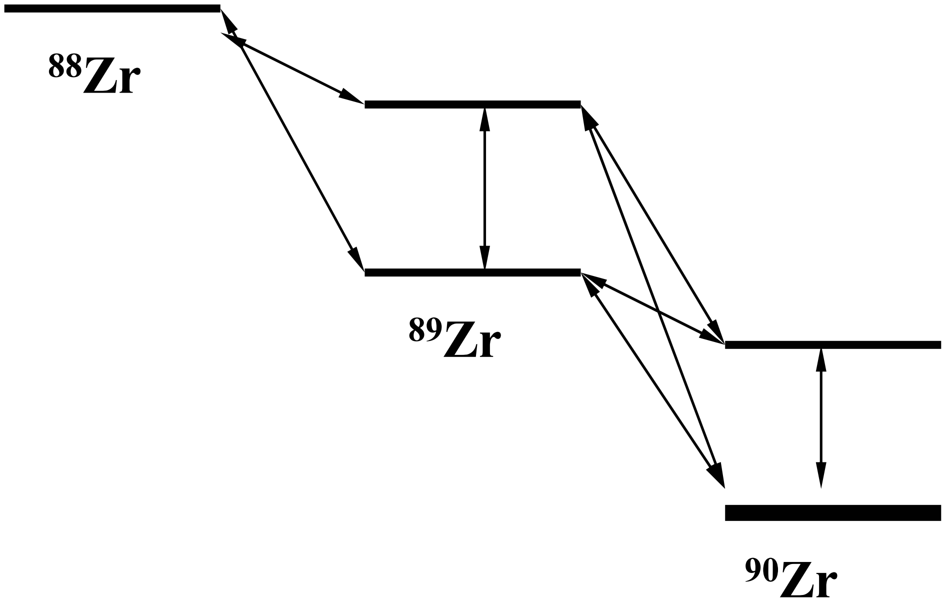
Surrogate Cross Section Measurements using Radioactive Beams

The Recyclotron Project at LBNL

Peggy McMahan
Lawrence Berkeley National Laboratory
Nuclear Science Division

Data Needs for Science-based Stockpile Stewardship [SBSS}

Certain elements are used as neutron flux monitors in brief, intense neutron flux environments.



Example – Zirconium

1. Begin with only ^{90}Zr.
2. Neutron flux induces nuclear reactions.
3. Measuring ratios such as ^{88}Zr/^{89}Zr gives info on neutron flux

Neutron cross-sections must be known accurately!

Direct neutron measurements on radioactive targets are *VERY* difficult

Multiple Steps

- Production
  - Need high intensity light ion accelerator
- Target Chemistry
  - Considerable radiation safety issues
  - Target purity issues
- Neutron bombardment
  - Need neutron facility close to production accelerator (proximity is half-life dependent)
- Off-line Counting
  - Need low background, well calibrated facility available for extended period of time

Example: Measure of $^{89}Zr(n,2n)^{88}Zr$ and $^{89}Zr(n,np)^{88}Y$ Cross Sections

1. Production of ^{89}Zr in the $^{89}Y(p,n)$ reaction

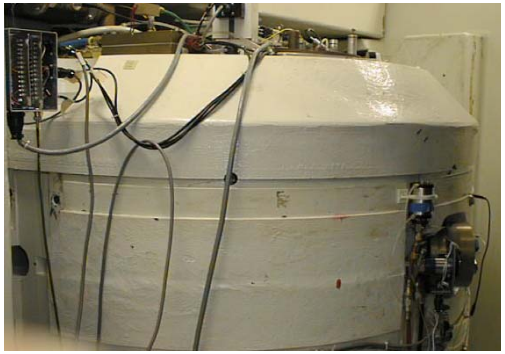
   $t_{1/2}$ = 3.27 days

2. Chemical Separation of Zr and Y

   Radioactivity ~ 1 Ci

3. Neutron Irradiation

4. Gamma-ray Counting of ^{89}Zr (for half-life measurement), ^{88}Zr (n,2n product) and ^{88}Y (n,np product)



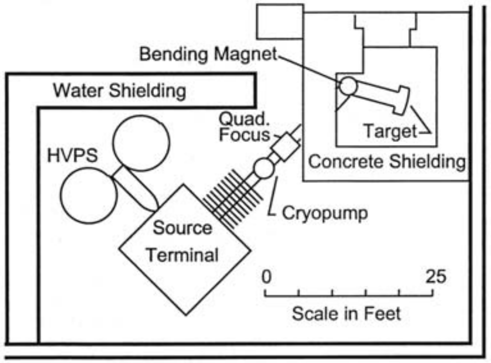


Figure 1. Major Components of RTNS Facility.

1. Biomedical Isotope Facility (BIF), LBNL

40 μA, 11 MeV protons

2. Hot cells at BIF, LBNL

3. Rotating Target Neutron Source (RTNS), UCB

10^{10}/sec 14-15 MeV neutrons

4. Gamma ray counting facility, LLNL

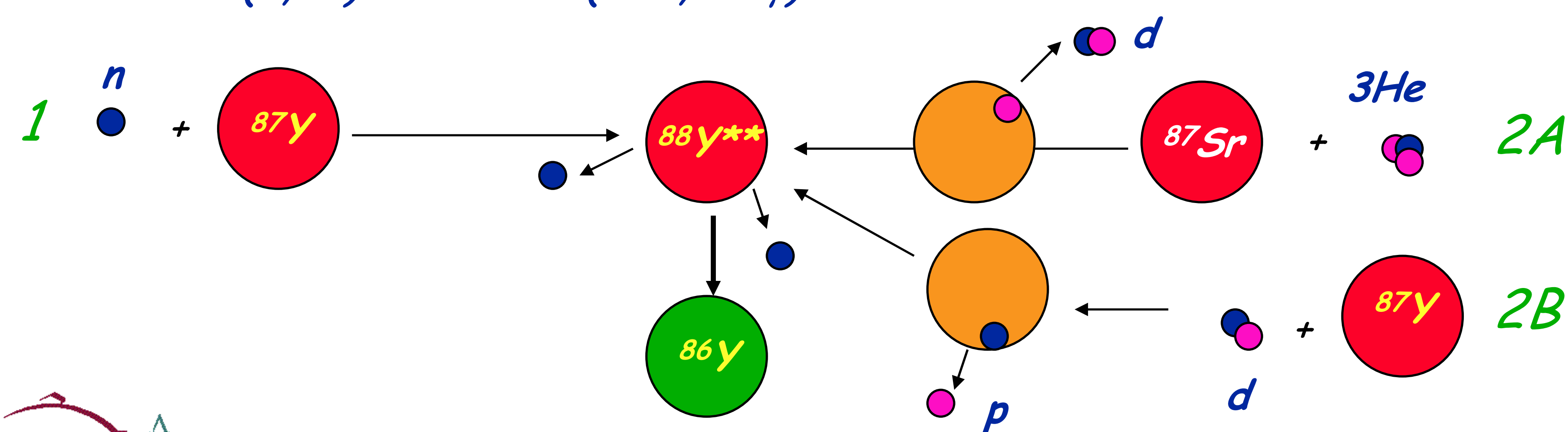
Paths to neutron cross sections of unstable species

1. Neutron measurements on radioactive targets

   EXAMPLE:

   $^{87}Y(n,2n)^{86}Y \Leftrightarrow {}^{87}Sr(^{3}He,d2n\gamma)^{86}Y$

2. Surrogate charged-particle reactions
   A. Normal kinematics on stable or unstable targets
   B. Inverse kinematics with stable or radioactive beams



Surrogate Reactions around A=80

- [d,p] neutron transfer to CN
  - best angular momenta and energy match
  - Intense beams available for normal kinematics
  - Requires same target as neutron measurement

  $\Rightarrow$ advantageous in inverse kinematics with RIBs
- [^{3}He,d] proton transfer to CN
  - Higher angular momenta and excitation energies $\Rightarrow$ more modeling involved
  - Intense beams available for normal kinematics
  - For odd Z CN, have more stable targets isotopes available

  $\Rightarrow$ advantageous in normal kinematics with stable or long-lived radioactive targets

Possible Reactions - Yttrium

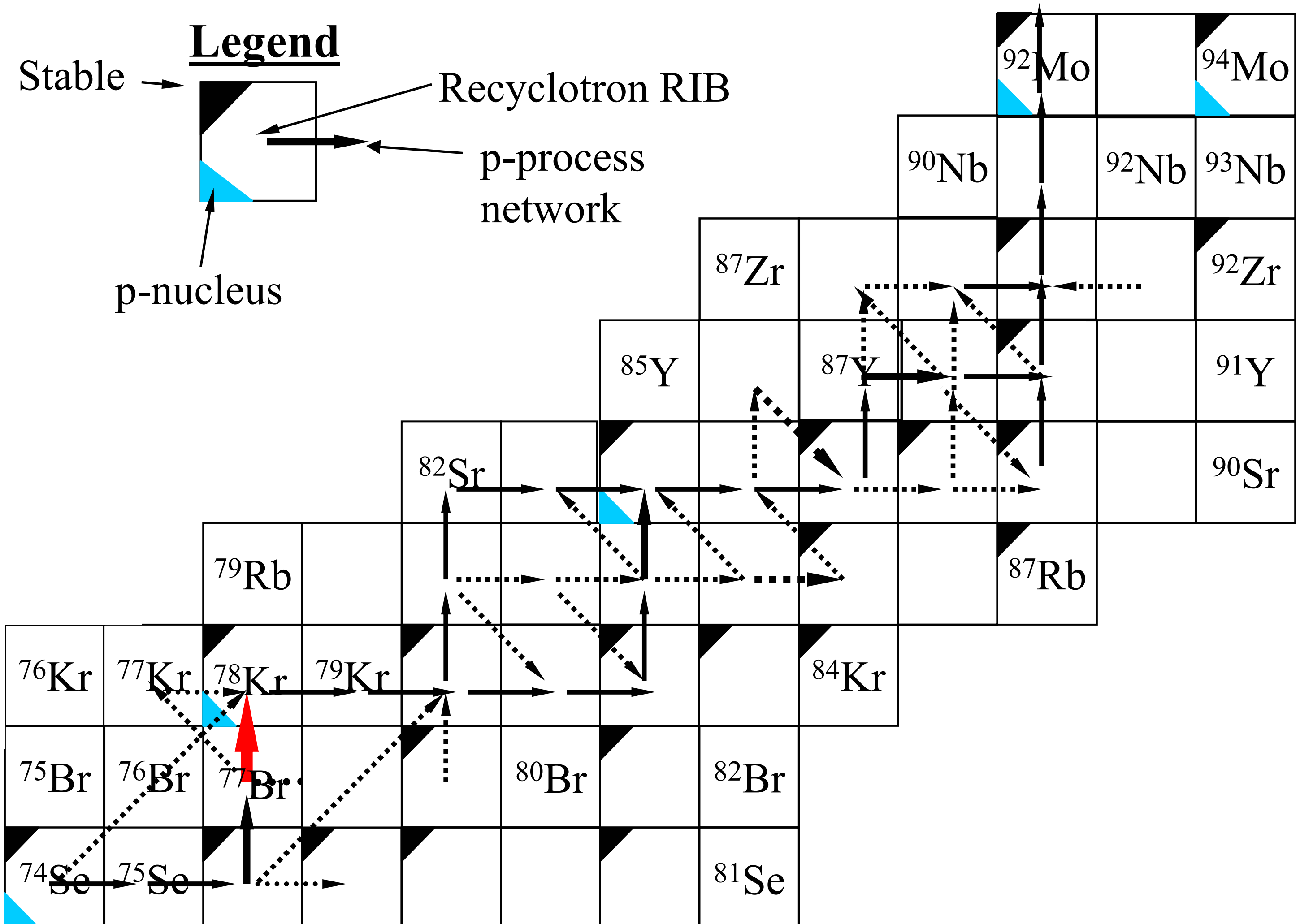
Target for (n,2n), (n,γ), (n,n′)	Half-life	[d,p] target	[^{3}He,d] target
^{86}Y	14.7h	^{86}Y	^{86}Sr
^{87}Y ^{87m}Y	79.8h 13.4h	^{87}Y	^{87}Sr
^{88}Y [1]	106.6d	^{88}Y	^{88}Sr
^{89}Y [2]	stable	^{89}Y	^{89}Sr
^{90}Y	64.1h	^{90}Y	^{90}Sr
^{91}Y	58.5d	^{91}Y	^{91}Sr
^{92}Y	3.54h	^{92}Y	^{92}Sr

1] (n,2n) measurement: D.R. Nethaway and M.Mustafa, UCRL-ID-133269 (1989)
2] all neutron measurements: M. Wagner et al, Ann Nucl. Eng. 16, 623 (1989)

Possible Reactions - Zirconium

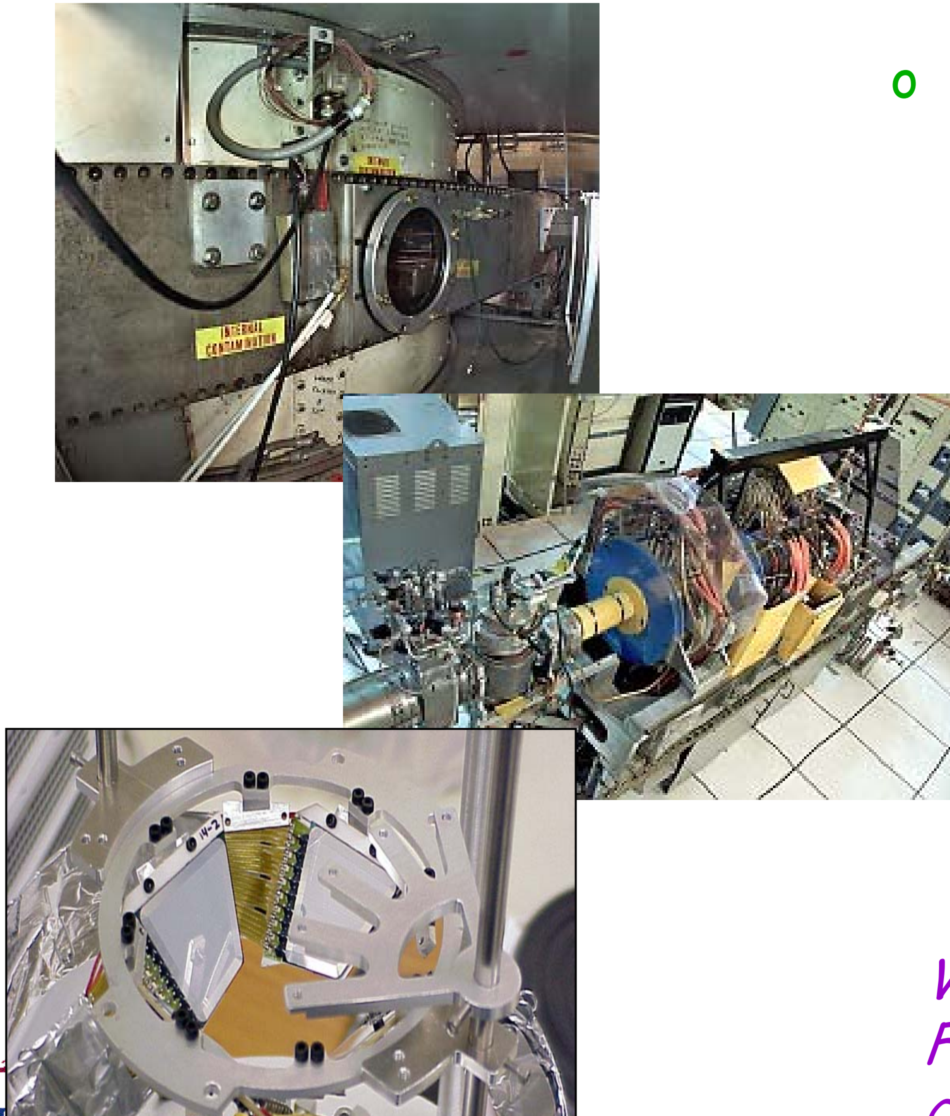
Target (n,2n), (n,γ), (n,n')	Half-life	[d,p] target	[^{3}He,d] target
^{86}Zr	16.5h	^{86}Zr	^{86}Y
^{87}Zr	1.71h	^{87}Zr	^{87}Y
^{88}Zr	83.4d	^{88}Zr	^{88}Y
^{89}Zr	3.27d	^{89}Zr	^{89}Y
^{90}Zr	stable	^{90}Zr	^{90}Y
^{91}Zr	stable	^{91}Zr	^{91}Y
^{92}Zr	stable	^{92}Zr	^{92}Y

*Nucleosynthesis of light p-nuclei in SNII neutrino driven winds**



*R.D. Hoffman et al., Ap.J. 460 478 (1996)

The 88-Inch Cyclotron is Alive and Well



- High-intensity light ion beams
  - Unstable beam and target production
  - Direct charged particle measurements
  - Surrogate measurements in normal kinematics
  - Produce quasi-monoenergetic neutron beams (under construction)
- AECR-U
  - high ionization efficiency for RIBs
  - Low and high temp ovens available

We're no longer a National User Facility, but funding is in place to continue operation.

Three ways to use the 88-Inch Cyclotron

1. Measure neutron cross sections directly
   - Intense deuteron beams allow production of quasi-monoenergetic neutron beams with good intensity
   - Short-lived radioactive targets can be made using high-intensity light-ion beams
2. Surrogate measurements in normal kinematics
   - High-intensity light-ion beams combined with STARS and clover detectors (e.g. Bernstein talk) on stable targets
3. Surrogate cross section measurements in inverse kinematics
   - Recyclotron beams of medium-lifetime species on solid or gas targets

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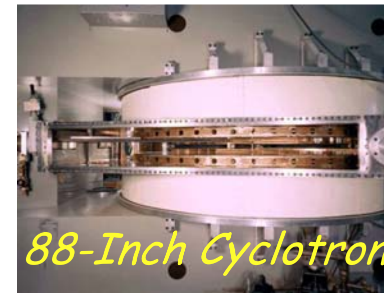
Making intermediate mass RIBs using the Recyclotron Technique

- A high-production cross section reaction is used to make a large number (10^{14-17}) of radioactive nuclei.
- The radioactive nuclei are removed from the target using either physical (boiling) or chemical means.
- These nuclei can then be re-injected into accelerator for use in RIB experiments.
- RIB intensities are influenced by several factors:
  - Lifetime
  - Primary beam current
  - Production cross section
  - Ease of extraction

First successful beam: ^{76}Kr

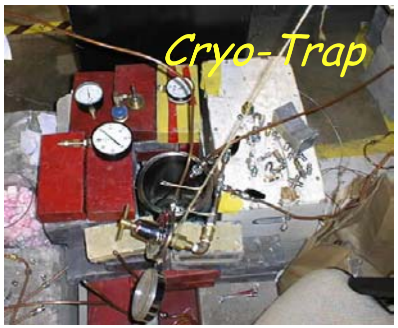
August 2003 - g-factor measure of ^{76}Kr (Rutgers, LLNL, LBNL)



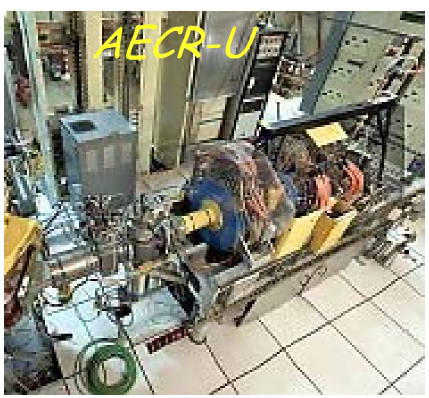
55 MeV $^{4}He^{+}$

He-jet

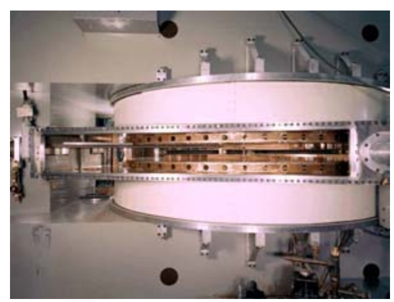
Kr/Br



Injection



Ionization

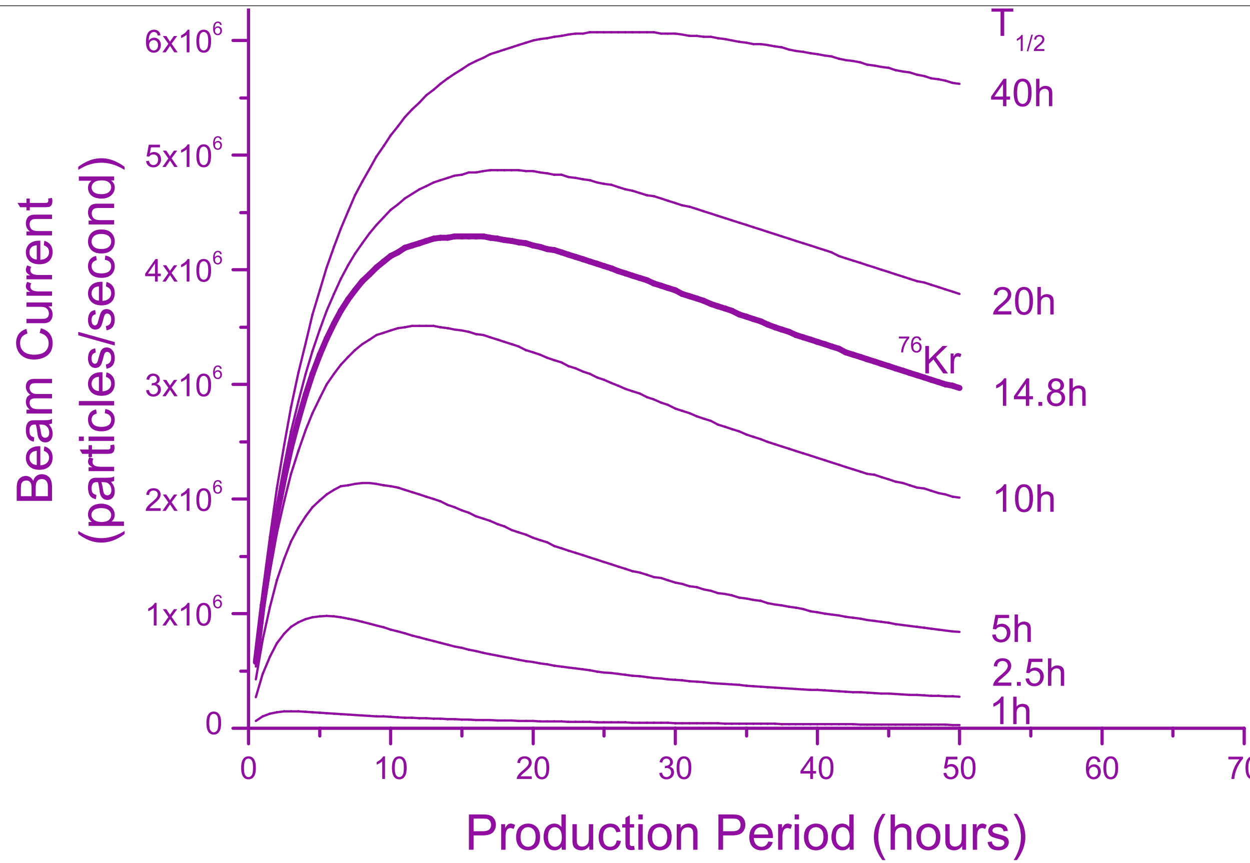


Acceleration

^{76}Kr to Cave 4C

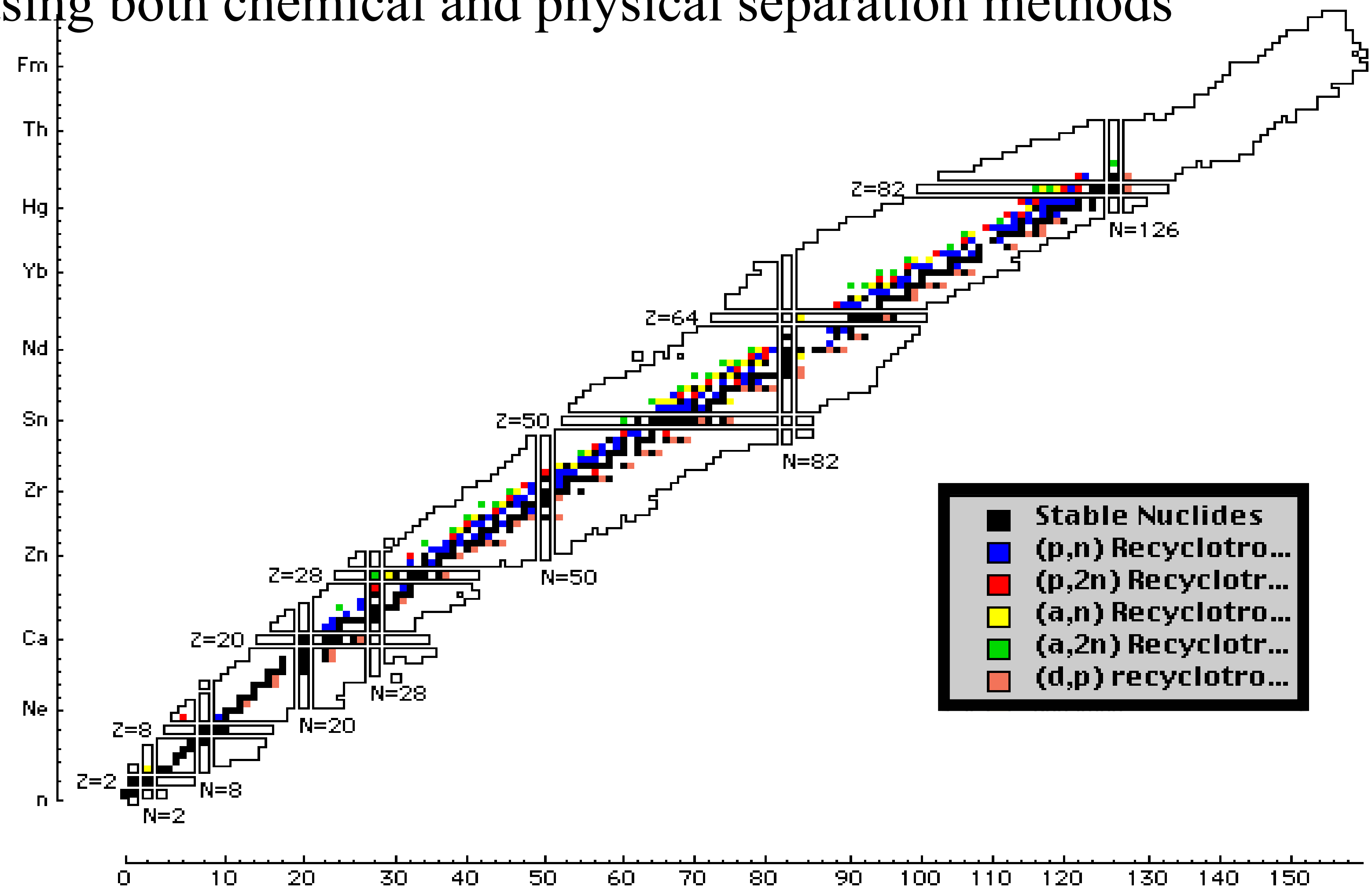
magnetic moment measurement

Batch	Production Period (hours)	Average Current (p A)	^{76}Kr atoms PACE	^{76}Kr atoms in trap	Production efficiency (%)	^{76}Kr through cyclotron	AECR-U+cyclotron efficinecy (%)
1	39	5.0(5)	$4.3(4)\times10^{14}$	$1.0(3)\times10^{14}$	23(7)	$2.0(4)\times10^{11}$	0.20(7)
2	15	5.6(5)	$2.9(3)\times10^{14}$	$3.4(9)\times10^{13}$	12(3)	$7(2)\times10^{11}$	2.2(8)
3	17	6.0(5)	$3.6(4)\times10^{14}$	$4.3(9)\times10^{13}$	12(3)	$6(2)\times10^{11}$	1.4(6)



Potential re-cyclotron beams

using both chemical and physical separation methods



Many beams possible over the entire chart of nuclides

The Collaboration

- LBNL
  - Peggy McMahan
  - James Powell
  - Charles Silver
  - Daniela Wutte
- LLNL
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  - Jeff Cooper
  - Larry Ahle
  - D. Dashdorj
  - Andreas Schiller
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